# Lecture #23 Langmuir Probes, Atomic Processes, and Plasma Generation
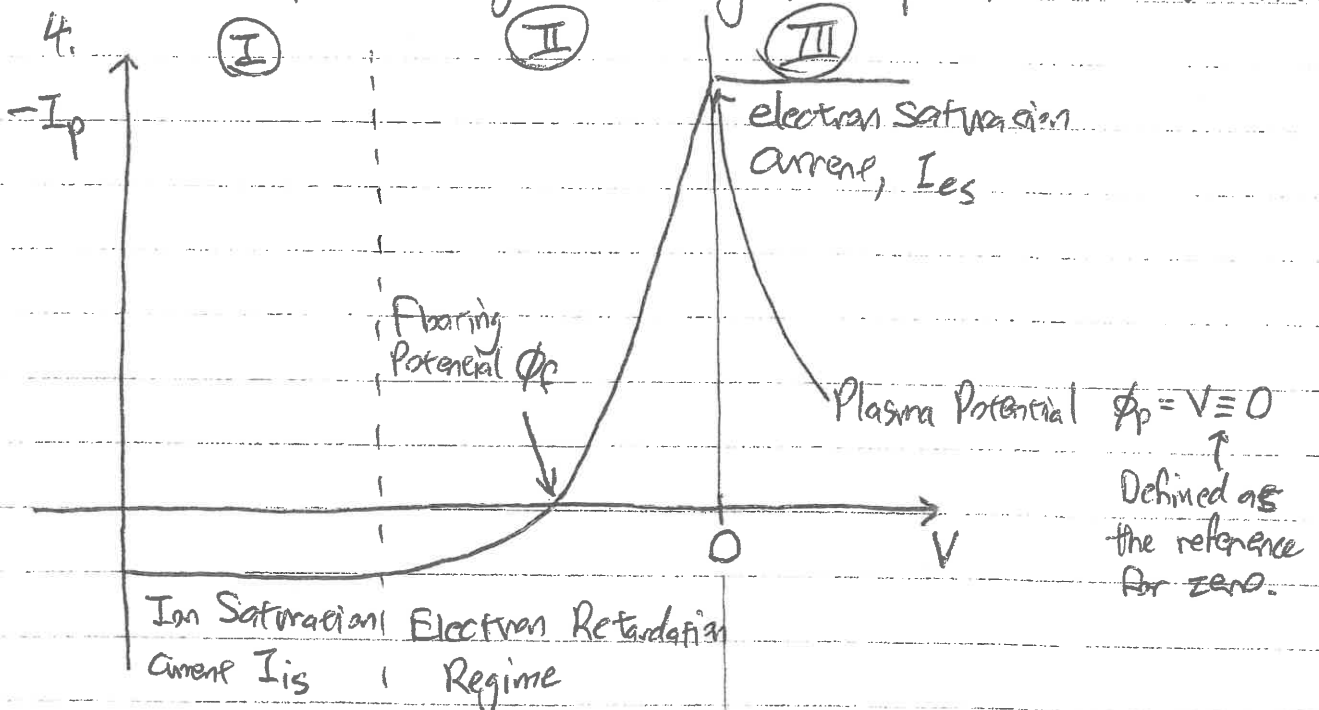
I. Langmuir Probes

A. Diagnostic of Electron Temperature T_e and Density n_e

1. Langmuir probes are small metal electrodes inserted into a plasma

2. For a cool, low density plasma, it enables one to determine electron temperature T_e and electron density n_e

Probe Current I_p

Probe Voltage, V

R_D

Discharge Voltage, V_D
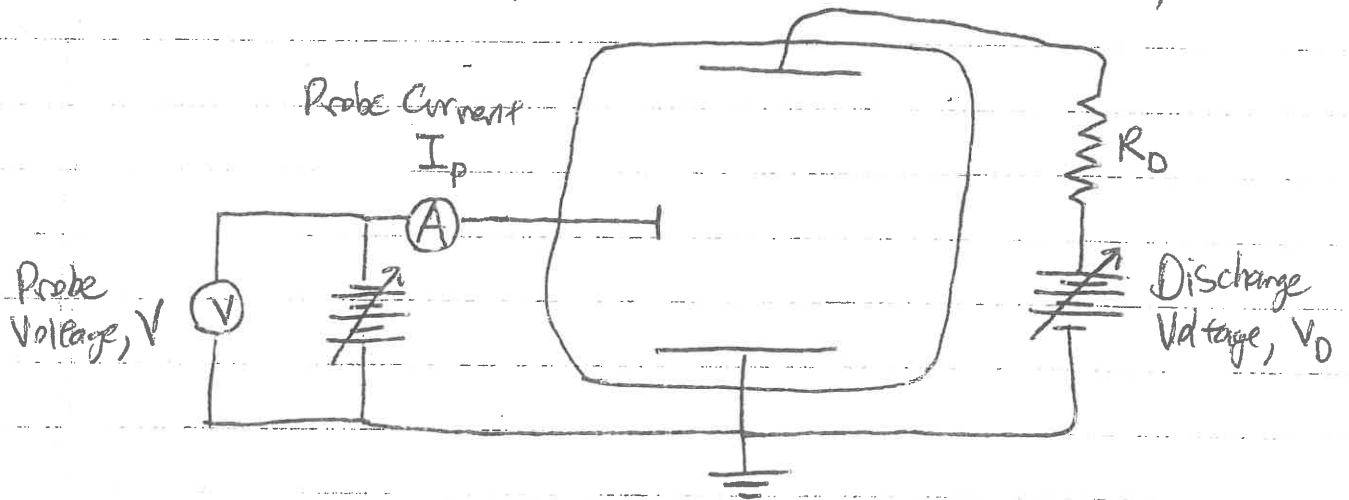
3. Sweep probe voltage from negative to positive and measure current I_p

4.

Ⅰ   Ⅱ   Ⅲ

$-I_p$

electron saturation current, I_{es}

Floating Potential ϕ_F

Plasma Potential $\phi_p = V \equiv 0$

↑ Defined as the reference for zero.

O V

Ion Saturation Current I_{is} Electron Retardation Regime

2. (Continued)

B. __Ion Saturation Current__

1. For a sufficiently negative probe potential, all electrons are prevented from reaching the probe, and you only get the ion current

2. From our study of the plasma sheath, we know the ion current is constant across the sheath (from the ion continuity equation). The ion current is therefore determine by the conditions at the sheath edge:

$$I_{is} = n_d e U_0 A,$$ where the ~~Bohm criterion~~ specifies

$$U_0 = c_s = \sqrt{\frac{T_e}{m_i}}$$

Probe surface area

3. But, we want to know the density in the unperturbed plasma, not the density at the sheath edge:
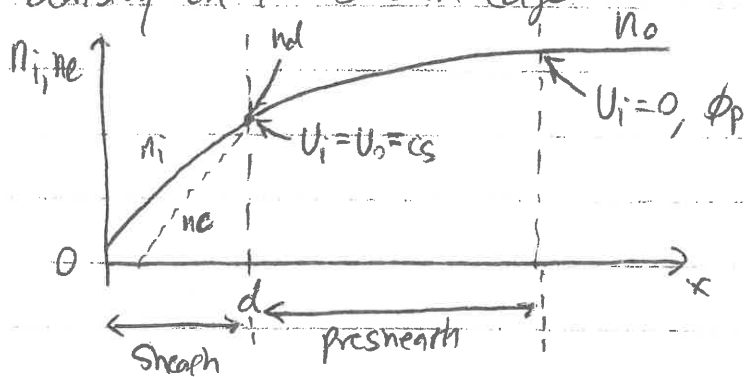
a. The ion momentum equation gives a conservation of energy condition that we can use to find n_d as a function of n_0.

$$\underbrace{\frac{1}{2}m_i U_0^2 + e\phi(d)}_{\text{Sheath edge}} = \underbrace{\frac{1}{2}m_i v_i^{\cancel{2}} + e\phi_p}_{\text{unperturbed plasma}}$$

b. Taking $\phi_p = 0$ as reference for potential [different from $\phi(d)=0$ choice last lecture],

we get $$\phi(d) = -\frac{1}{2}\frac{m_i U_0^2}{e} = -\frac{1}{2}\frac{m_i}{e}\frac{T_e}{m_i} = -\frac{T_e}{2e}$$

I.B. (Continued)

   3. (Continued) c. In presheath $n_i = n_e = n_0 e^{\frac{+e\phi}{T_e}}$, where the
density n_0 is unperturbed plasma density at $\phi = \phi_p = 0$.

   d. Substituting $\phi(d) = -\frac{T_e}{2e}$, we get $n_i(d) = n_0 e^{\frac{e\left(\frac{-T_e}{2e}\right)}{T_e}} = n_0 e^{-\frac{1}{2}} \approx 0.61 n_0$

                                                            Density at
                                                            sheath edge

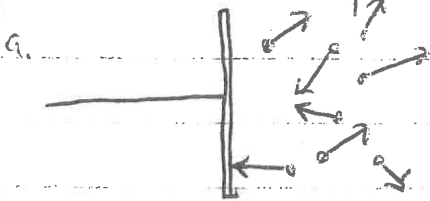   4. Therefore,

$$\boxed{I_{is} = 0.61 n_{io} e \sqrt{\frac{T_e}{m_i}} A}$$

If we can find T_e, this gives n_{io}!
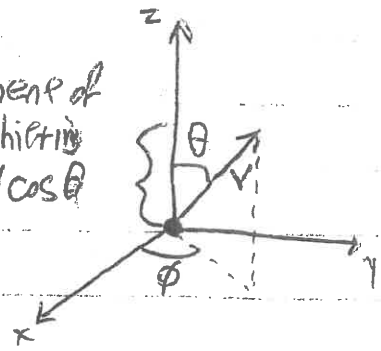
C. Electron Saturation Current

   1. For a probe voltage that is positive w.r.t. plasma potential $\phi_p \equiv 0$, electrons are not hindered from reaching the probe.

      $\Rightarrow$ There is no sheath formation.

   2. All electrons in positive half-plane of Maxwellian distribution will reach the probe.

   a.

                                   b. Component of velocity hitting probe, $v\cos\theta$

   3. We must integrate over half plane of distribution $f_e(v) = \frac{n_{oe}}{\pi^{\frac{3}{2}} v_{ee}^3} e^{-\frac{v^2}{v_{ee}^2}}$

   a. $I_{es} = -eA \int_{half\ plane} d^3\underline{v}\ v\cos\theta f_e = -eA \underbrace{\int_0^{2\pi} d\phi}_{=2\pi} \underbrace{\int_0^{\frac{\pi}{2}} d\theta \sin\theta \cos\theta}_{=\frac{\sin^2\theta}{2}\Big|_0^{\frac{\pi}{2}} = \frac{1}{2}} \underbrace{\int_0^\infty dv \frac{v^3 e^{-\frac{v^2}{v_{ee}^2}}}{\pi^{\frac{3}{2}} v_{ee}^3} n_{oe}}_{\frac{v_e n_{oe}}{\pi^{\frac{3}{2}}} \int_0^\infty dy\ y^3 e^{-y^2} = \frac{1}{2} \frac{v_{ee} n_{oe}}{\pi^{\frac{3}{2}}}}$

                $= -eA(2\pi)\left(\frac{1}{2}\right) \frac{v_{ee}\ n_{oe}}{2\ \pi^{\frac{3}{2}}} = -\frac{eA n_{oe}}{2\pi^{\frac{1}{2}}} \sqrt{\frac{2T_e}{m_e}}$

   b. Thus
$$\boxed{I_{es} = -\frac{1}{2} n_{oe} e \left(\frac{2T_e}{\pi m_e}\right)^{\frac{1}{2}} A}$$

I. C. (Continued)

4. NOTE: Ratio $\dfrac{|I_{es}|}{I_{is}} = \dfrac{+\frac{1}{2} n_{0e} e \left(\frac{2T_e}{\pi m_e}\right)^{\frac{1}{2}} A}{0.61 m_{i0} e \left(\frac{T_e}{m_i}\right)^{\frac{1}{2}} A} = \dfrac{1}{0.61 (2\pi)^{\frac{1}{2}}} \sqrt{\dfrac{m_i}{m_e}}$

Quasineutrality — $n_{0e} c = n_{0i} e = 0$

So $\dfrac{|I_{es}|}{I_{is}} = 0.65 \left(\dfrac{m_i}{m_e}\right)^{\frac{1}{2}}$. Since $m_i \gg m_e$, $|I_{es}| \gg I_{is}$.

D. Electron Retardation Current

1. In this regime, it can be shown that:

a. $I_e(V) = I_{es}\, e^{\frac{e(V-\phi_p)}{T_e}} = I_{es}\, e^{\frac{eV}{T_e}}$

2. Taking the $\ln$ of this equation, we find:

$\ln(|I_e|) = \ln(|I_{es}|) + \dfrac{e}{T_e} V$

← slope is inversely proportional to T_e
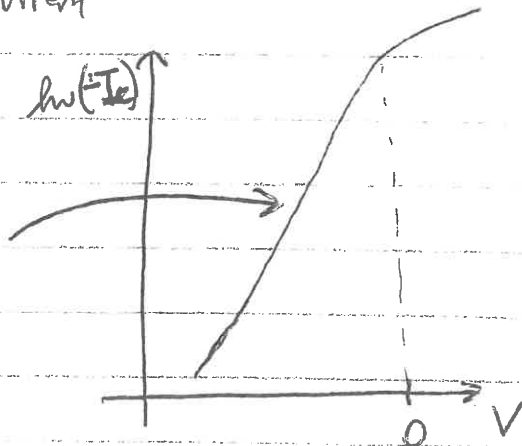
3. To determine the electron temperature:

a. Determine ion saturation current I_{is}

b. $\underbrace{I_e(V)}_{\substack{\text{electron}\\\text{current}}} = \underbrace{I_p(V)}_{\substack{\text{probe}\\\text{current}}} - \underbrace{I_{is}}_{\substack{\text{ion}\\\text{current}}}$

c. Plot a semi-log plot
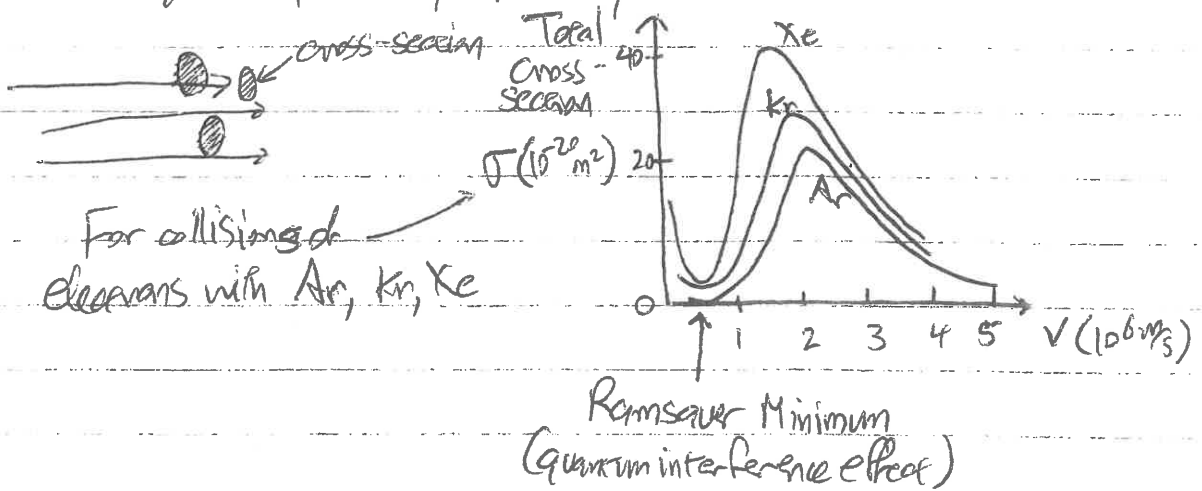
Slope $= m = \dfrac{e}{T_e}$

$\boxed{T_e = \dfrac{e}{m} \leftarrow \text{slope}}$

II. Atomic Collisional Processes

A. Cross-Sections

1. Collisions between charged particles (usually electrons) and neutral atoms can lead to ionization of the atom

2. Such collisional ionization is an important way to generate plasmas.

3. We quantify the probability of collisions as a cross-section, σ

cross-section

Total Cross-Section

$\sigma (10^{-20} m^2)$

For collisions of electrons with Ar, Kr, Xe

Xe
Kr
Ar

$V (10^6 \, m/s)$

Ramsauer Minimum
(Quantum interference effect)

4. For a gas of atoms with density n_a,

a. Mean free path $\lambda_{mfp} = \dfrac{1}{n_a \sigma}$

b. Collision frequency $\nu_{coll} = \sigma \, V \, n_a$

collision cross-section   velocity of charged particle

B. Ionization Rate Coefficient

1. If we want to know the rate of ionization in a gas with electron temperature T_e, we must average over velocity distribution,

$$f_e(v) = \frac{n_e}{\pi^{\frac{3}{2}} v_{Te}^3} e^{-\frac{mv^2}{2T_e}} \qquad v_{Te}^2 = \frac{2T_e}{m_e}$$

2. Rate coefficient is defined as the average over distribution

$$\langle \sigma_{ion} v \rangle = \frac{1}{n_e} \int_0^\infty \sigma_{ion}(v) \, v \, f_e(v) \, dv$$

Lecture # 23 (Continued)

II. B. (Continued)

3. The _ionization frequency_ is then $\nu_{ion} = n_a \langle \sigma_{ion} v \rangle$
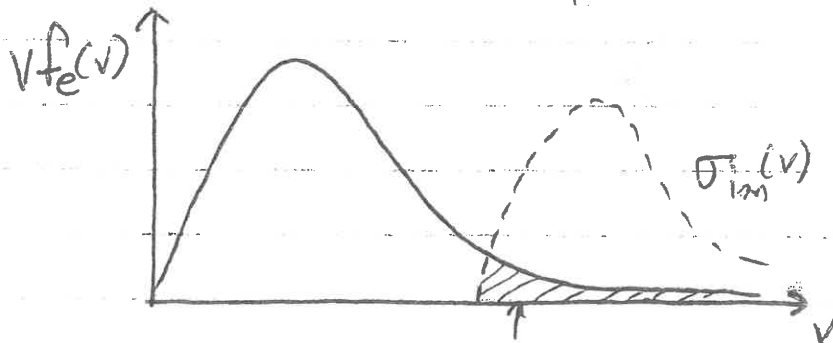
4. Total Ionization rate (per volume per second)

$$S_{ion} = n_e n_a \langle \sigma_{ion} v \rangle$$

C. Electron Impact Ionization

1. a. Typical low pressure gas discharges have $T_e \sim 3 eV$

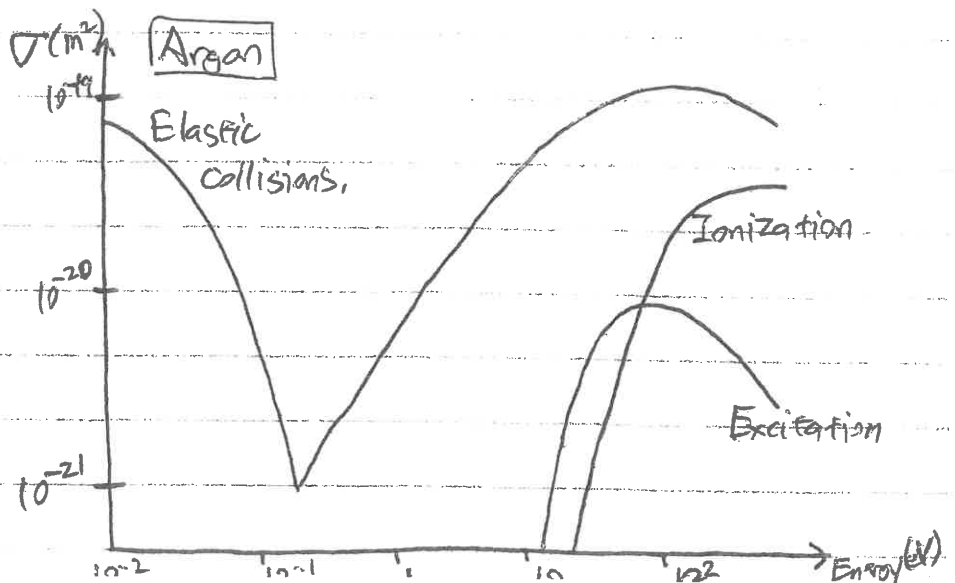b. But ionization energy is much larger, e.g. for argon, $15.8 eV$

2. Ionization rate is determined by tail of distribution

High energy electrons in
tail are responsible for ionization.

3. For electron collisions
with atoms, other
processes can occur:

a) Elastic collisions
b) Ionization
c) Excitation

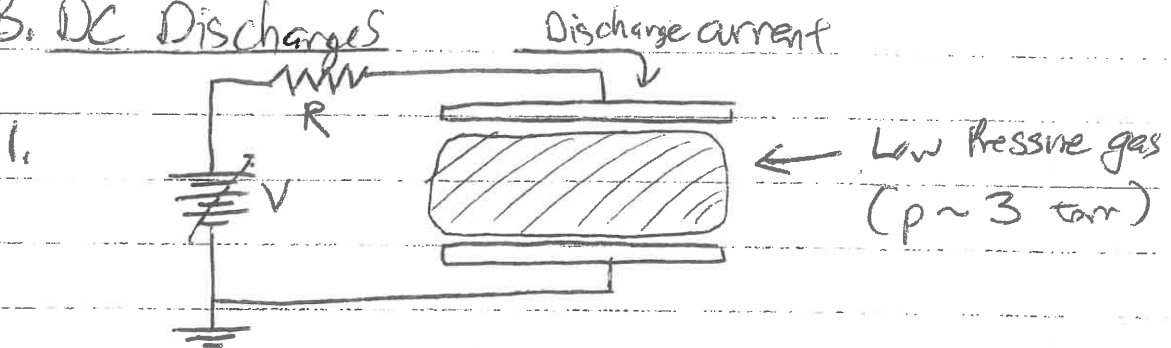Lecture #23 (Continued)

III. Plasma Generation

  A. General Types of Discharges
    1. DC Discharges
    2. Capacitive RF Discharges
    3. Inductively Coupled Discharges

  B. DC Discharges

  1.

Discharge current

Low Pressure gas
$(p \sim 3 \text{ torr})$

    a. Power supply chosen high enough so breakdown occurs, $V \sim 600V$
    b. Resistor in series to limit current after breakdown.

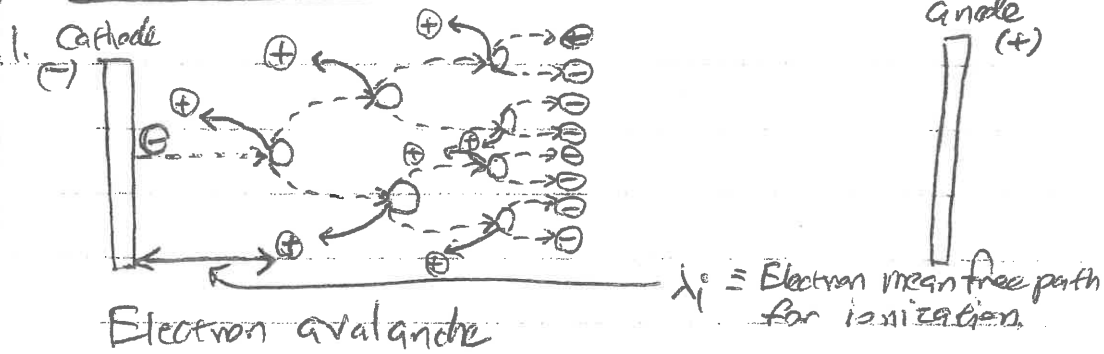 2. Glow discharge in long glass tube: (Fluorescent or neon lights)

Cathode
(—)

anode
(+)

Cathode   negative   positive column   anode
layer   glow   glow

ϕ

E
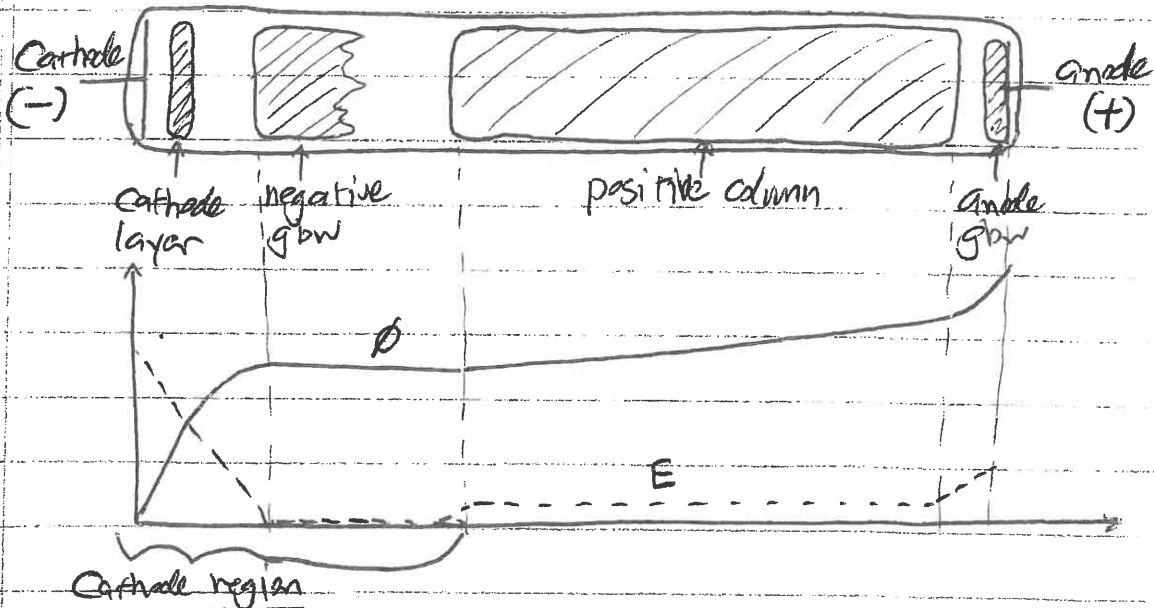
Cathode region

liberates electrons
from cathode to cause
electron impact ionization

III. C. Gas Breakdown

1. Cathode

Electron avalanche

λ_i = Electron mean free path for ionization
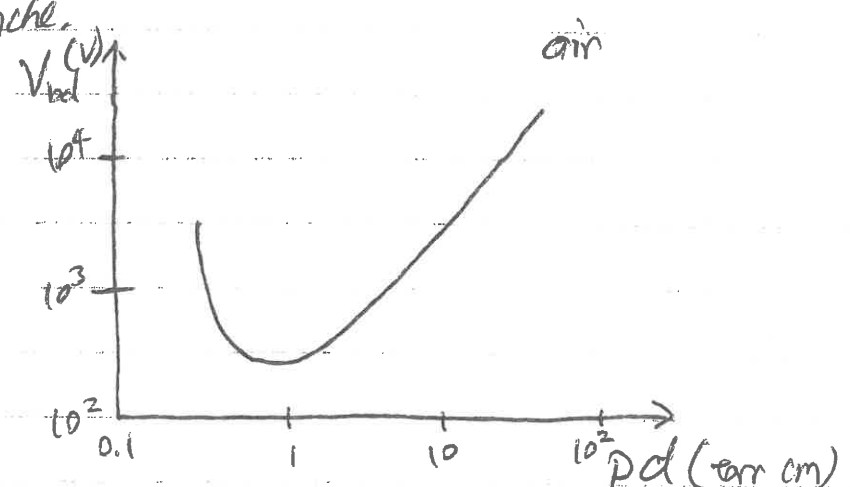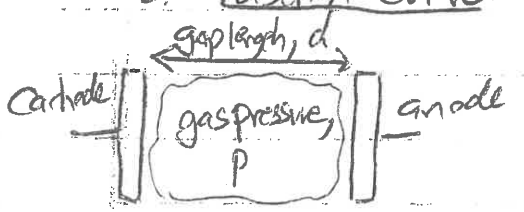
2. a. Ions released from ionization collisions impact the cathode
   b. These ion impacts can release more electrons to continue the process
   c. Breakdown occurs when enough electrons are released to maintain the avalanche.

3. Paschen Curve:

gap length, d

Cathode | gas pressure, P | anode

a. Minimum in breakdown voltage vs. (pressure)×(gap length)
b. Left of minimum, too few atoms for ionization
c. Right of minimum, energy gain per mean free path is too little energy for ionization
d. Hence, a higher electric field is required for breakdown.

4.

| Gas	Cathode	V_{min} (V)	$(pd)_{min}$ (torr cm)
He	Fe	150	2.5
Ar	Fe	265	1.5
Air	Fe	330	0.57
Hg	W	425	1.8

III. D. Thermionic Emitters

   1. Cold cathodes require high voltages (300 - 3000 V) to achieve breakdown

   2. Heated cathodes can release electrons more readily, requiring a smaller voltage drop.

   3. Hot metal or oxide cathodes: W, LaB_6, $BaSrO$

E. Capacitive Radio-Frequency (RF) Discharges

   1. Parallel plate discharge, $f = 13.56$ MHz

   2. Electrons gain a thermal energy of a few eV, enough to lead to ionization

   3. Frequently used for plasma processing: a) plasma etching
      b) Plasma-enhanced chemical vapor deposition (PECVD)

   4.
     ← sheath
     ← Maxima of glow adjacent to each electrode
     ← sheath
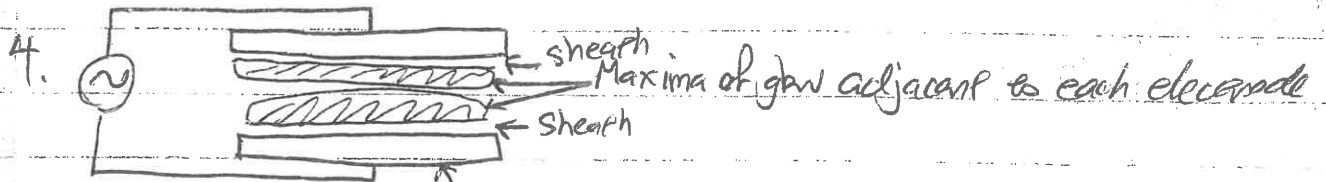
   RF electric fields result from surface charges on electrodes.

F. Inductively Coupled Plasmas

   1. Can achieve higher plasma densities for plasma processing in semi-conductor industry

   2.
   ← Spiral coil
   quartz window →
   plasma
   substrate
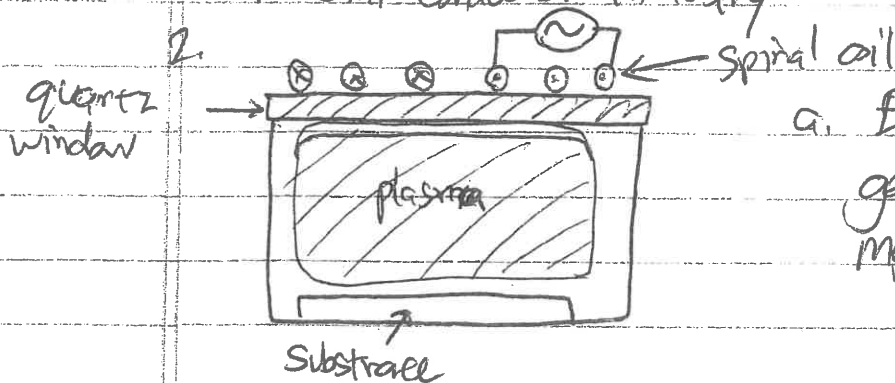
     a. Electric field in plasma is generated by a time-varying magnetic field